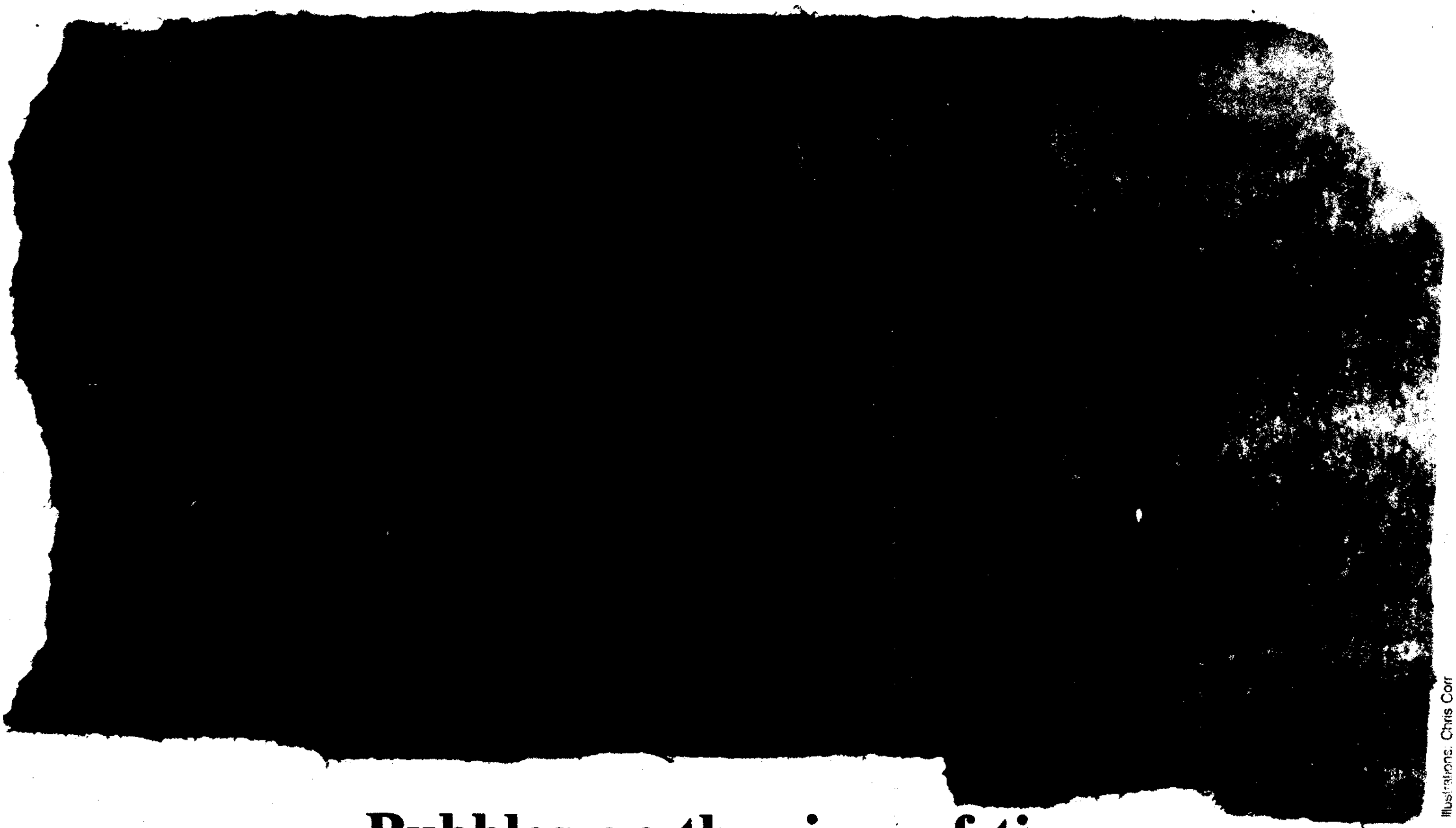


Illustrations: Chris Corr

Bubbles on the river of time

The latest ideas in cosmology do away with the concept of a "moment of creation". Instead, our Universe becomes one bubble in an eternal, infinite foam

John Gribbin

"MANY and strange are the universes that drift like bubbles in the foam upon the River of Time." Arthur C. Clarke wrote those words, in 1949, as the opening to a science fiction story called *The Wall of Darkness*. In 1988, they would stand as an accurate description of modern cosmological thought. During the past few years, favoured theories of the evolution of the Universe have changed dramatically. Having developed a satisfactory explanation of how the Universe expanded from the fireball of a hot big bang to become as we see it today, cosmologists joined forces with particle physicists to try to understand the moment of creation itself. What they have found is that this may not have been a unique event, and that our Universe may be just one bubble among many in the foam on the river of time.

"The Universe" is everything we can see or have direct knowledge about, so it might seem strange to talk about the existence of "other universes". Such speculations belong, at first sight, in the realms of metaphysics or science fiction, not in the scientific world of physics and astronomy. But it is, in fact, the study of our Universe, the totality of everything we can have knowledge of, that now leads sober scientists to speculate that other universes may, indeed, exist.

The standard theory of the big bang describes the expansion of our Universe from a state when its density was comparable with that of nuclear matter today. The picture derives from the observed fact that the Universe is expanding. If we imagine reversing this expansion, and tracking the evolution of the Universe backwards in time, then everything must have been concentrated in a single mathematical point of infinite density, a singularity, about 15 billion years ago. Without quite going that far, astronomers and physicists in the 1960s and 1970s left the meaning of that "moment of creation" to one side, and considered how the Universe would have evolved from a superdense state, a fraction of a second after the outburst from the singularity.

One of the most dramatic achievements of science is the resulting description of everything that has happened since 0·0001 second after the singularity, when the density was 10^{14} grams per cubic centimetre—the density of an atomic nucleus and the temperature was 10^{12} K, in terms of the known laws of physics. This standard model explains how 25 per cent of the original hydrogen was converted into helium in the big bang, why the Universe is suffused with a faint background of cosmic radiation at a temperature of just under 3 K, and much more besides. The standard model could not explain, however, the moment of creation itself—how the superhot, superdense Universe with an "age" of 0·0001 second came into being. In probing that mystery, theorists are considering the possibility that our Universe is just one bubble amongst many in some greater suprauniverse.

These ideas are connected with the concept of inflation. Inflation explains the present smoothness and uniformity of the Universe in terms of a burst of exponential expansion that occurred shortly after the moment of creation and just before the fireball stage that represents the big bang proper. Inflation began when the entire Universe was packed into a volume comparable to that of an elementary particle (see Box). Inflation provides a way of obtaining something (the Universe) for nothing (out of the vacuum), by allowing a short-lived quantum fluctuation to grow indefinitely big.

Quantum fluctuations occur because there is no certainty in quantum physics; even death and taxes have only a high probability. In the most familiar example of quantum uncertainty, we can specify accurately the position of a particle such as an electron only at the cost of uncertainty about its momentum, and vice versa. You can know *either* where an electron is, *or* where it is going, but not both properties simultaneously. This uncertainty is not simply a deficiency of human measuring devices, but, as Werner Heisenberg showed, a fundamental law of nature. We call pairs of properties such as position–momentum, that exhibit this behaviour, conjugate variables. Energy and time form another pair of conjugate variables.

One way to interpret the energy–time uncertainty is to imagine a tiny volume of space, anywhere in the Universe. Ignoring any photons that happen to be passing through, we would say that this bit of space contains no energy. But quantum physics tells us that nothing is certain. This little volume *might* contain a certain energy, E, provided only it does so for less than a certain time, t. Quantum mechanics precisely define the relation between E and t; the bigger E is, the smaller t must be. Energy can appear in the little volume of space as long as it disappears again quickly, before the rest of the Universe has time to notice.

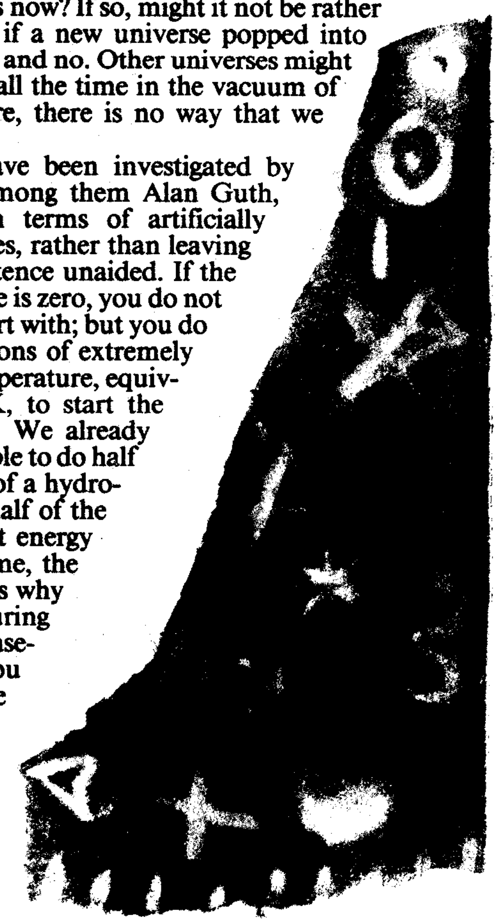
It sounds like abstract philosophising with no practical value, but it is not. Albert Einstein taught us that mass (m) and energy (E) are equivalent through the equation $E=mc^2$ where c is the velocity of light. So the uncertainty rules are actually saying that matter can appear in a suitably small volume of space, for a suitably short interval of time, provided it promptly vanishes again. If an electron and a positron, for example, popped out of the vacuum, led brief lives and annihilated one another, there would be no violation of any of the rules of physics. Such particles are called virtual pairs. Their existence explains the way the electromagnetic forces between charged particles work. Without allowing for virtual pairs, theory does not match observations. In that sense, virtual particles have been shown to be "real".

The smaller the energy involved, the longer the particles can live. In the early 1970s, Ed Tyron of the City University of New York realised that if zero energy were involved, then, in principle, the quantum fluctuation could live forever. A fluctuation that contained zero energy did not seem too interesting at first sight. But because of the way gravity works, the energy stored in a gravitational field has the opposite sign to the familiar Einsteinian mass–energy of a particle. If mc^2 is positive, then gravitational energy is negative. Tyron suggested that the total gravitational energy of the Universe and its total mass energy might be equal and opposite, so that the net energy of the Universe is zero. In that case, the whole thing could have appeared out of nothing as a quantum fluctuation.

In its original form, the trick did not work. Such an enormously massive fluctuation could occur in principle, but it would occupy a tiny volume of space, smaller than a proton, and it would, by definition, have an enormous gravitational field. The result would be an extremely rapid collapse, snuffing the embryonic universe out of existence as quickly as any pair of virtual particles. Inflation, however, provides a way out of this dilemma. In the tiny fraction of a second it exists, inflation can set to work and blow up the seed into a full-sized universe. "Full-sized," in this case, means something about as big as a basketball, containing as much mass–energy as the entire visible Universe and experiencing a big bang. All the rest follows naturally from the known laws of physics, as explained in standard models of cosmology.

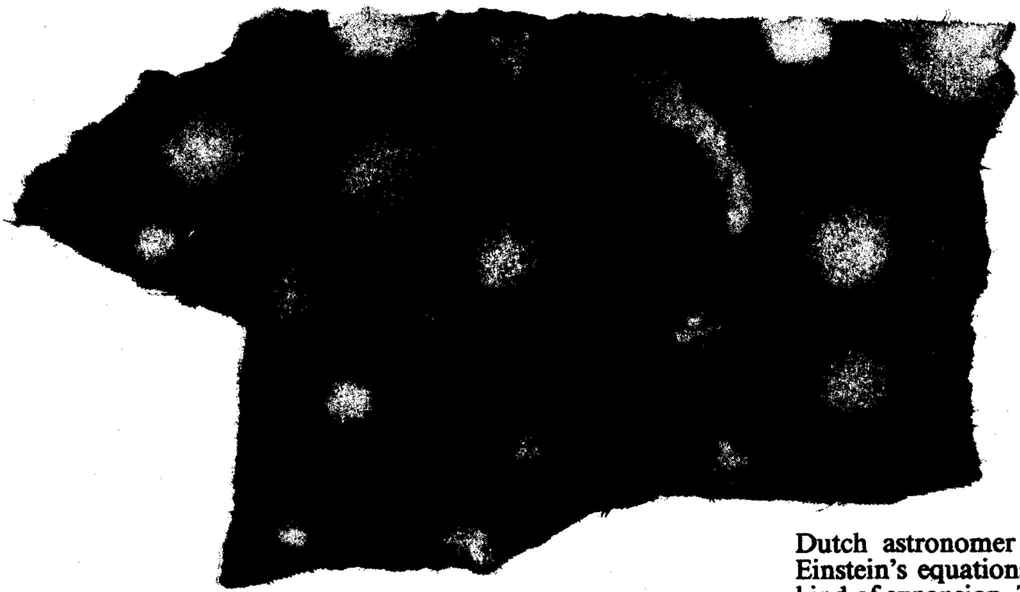
But why stop at one Universe? If bubbles of mass–energy can appear out of nothing at all, and explode exponentially into life as fully fledged universes, shouldn't the same processes—vacuum fluctuations—be going on in the space between the stars now? If so, might it not be rather uncomfortable for us if a new universe popped into existence nearby? Yes, and no. Other universes might indeed be being born all the time in the vacuum of space; but if they were, there is no way that we would know about it.

The possibilities have been investigated by several researchers, among them Alan Guth, who likes to talk in terms of artificially creating other universes, rather than leaving them to pop into existence unaided. If the net energy of a universe is zero, you do not need much mass to start with; but you do need to create conditions of extremely high density and a temperature, equivalent to about 10^{24} K, to start the inflationary processes. We already have the energy available to do half the trick, in the form of a hydrogen bomb; the other half of the trick is to confine that energy within a minute volume, the size of an atom. This is why nobody is manufacturing universes in their basement just yet. If you *could* confine the energy, though, what you ought to get, according to the equations of general relativity, is a black hole. Interesting in its own



right, but a black hole is not a new universe. Or is it?

Guth, and others, have shown that what happens inside the confined regions depends on exactly how the pressure is applied. In many cases, the compressed region does turn out to be "only" a black hole. But there are solutions to the equations that given their initial conditions, do allow for the prospect of inflation. The confined region does not, however, expand out into the Universe at large. Instead, it expands in a direction at right angles to our familiar dimensions of space and time, into a universe of its own. Exactly the same thing will happen to any inflationary seeds created by quantum flucutuations in the vacuum of our Universe.



Cosmologists often liken our expanding Universe to the skin of a balloon that is increasing in size. The two-dimensional skin of the balloon represents *all* of our familiar dimensions. As the balloon expands, the Universe gets bigger. Any "new" universes created within our Universe, either naturally or by someone with a hydrogen bomb in their basement, are like little bubbles in the skin of the balloon. They pinch off from our space-time (the skin of the balloon) and expand outwards in their own right, in their own space and their own time.

From our perspective, nothing seems to have happened. Perhaps a black hole has appeared, perhaps not. From the perspective of any observer able to withstand the extreme conditions inside the superdense region, however, things would be very different. The region would inflate exponentially, then go over into a big bang and expand more sedately. Stars, galaxies and intelligent creatures could evolve, study their surroundings and begin to wonder about the possibility of creating new universes in the basement. Quantum cosmology allows the possibility of creating not just one universe but an infinite number of universes out of nothing at all. The universes may be interconnected, in some complex way, as new universes are born within, but then pinch off from the vacuum of old universes, producing a complex, multidimensional foam. Our Universe may simply be a region of space-time that has pinched off from another bubble. The bubbles can never communicate with one another, and might have very different properties.

Richard Gott, an astrophysicist at Princeton, however, has come up with a similar scenario in which different universes can communicate with one another with potentially catastrophic results. Gott has taken the idea of inflation to extremes. Instead of envisaging a tiny burst of inflation for a split-second long ago, he suggests that our Universe may be embedded in an eternal sea of inflation. This larger "superspace" has always been expanding exponentially, and always will be. The strangest thing about this concept is that it dates back to 1917, when the Dutch astronomer Willem de Sitter found a solution to Einstein's equations of general relativity that describes this kind of expansion. The visible Universe clearly is not expanding at this furious rate, so, for 70 years, theorists ignored the equations describing what became known as "de Sitter space", until Gott took them up.

Gott makes an analogy between de Sitter space and a pot of boiling water. De Sitter space, which is in the superdense, superhot state appropriate to inflation, is always on the edge of forming bubbles of lower density, like bubbles of steam in the boiling water. The view from inside one of those bubbles would be the same as the view from our Universe now—a moment of inflation, followed by a slower, steady expansion into a state of lower density. As the de Sitter space is growing exponentially all the time, there is always more room between the bubbles where new bubbles can form. But the new bubbles appear at random, so there is always a possibility, however small, that a new bubble might begin to grow right next to our Universe, and expand into us.

The germination of a universe

THE UNIVERSE we see around us is smooth and uniform—it looks the same in all directions. This is surprising, because the Universe is so big. How does the cosmic background radiation on one side of the sky "know" the temperature it needs to have in order to match precisely the background radiation coming from the opposite side of the sky? When the photons from opposite sides of the sky arrive in our detectors, that is the first contact they have had with matter, according to the standard model of the big bang. The regions on opposite sides of the sky have always been farther apart than the distance light could have travelled since the big bang, at every stage of the universal expansion.

Inflation explains why the Universe is uniform. According to this idea, a single superforce split apart to produce the four forces we know today—gravity, electromagnetism and the strong and weak nuclear forces. It poured energy into the expansion of the Universe at a time corresponding to 10^{-34} seconds after the singularity at the moment of creation. As a result, the Universe doubled in size with every 10^{-34} seconds that passed. This may sound modest, but doubling *every* 10^{-34} seconds means, that in 10^{-33} seconds, the Universe underwent 10 doublings, increasing in size by a factor of 2^{10}. In 10^{-32} seconds, it increased in size by a factor of 2^{100}. In far less than the blink of an eye, a region 10^{-36} times the size of a proton was inflated into a volume 10 centimetres across, the size of a grapefruit. Inflation takes the vastly submicroscopic world of the early Universe and suddenly brings it up to the sort of dimensions we are familiar with, and that the standard model of the big bang can cope with.

Inflation was over less than 10^{-30} seconds after the singularity. It explains the uniformity of the Universe, because everything we can see was once a tiny, uniform seed in which there was literally no room for irregularities.

When space-time expands in this way, it is not restricted by Einstein's speed limit. The speed of light is the ultimate limit for anything moving *through* space; the expansion of the Universe was a stretching of space itself. Space (as well as time and matter-energy) was created when the Universe was born, and has been expanding ever since. □

The results would depend on just how soon after the new bubble broke through into our Universe after its birth. A large, old bubble might merge indistinguishably with ours. But a small, hot, vigorously expanding bubble would be another matter entirely. It would be like a hole in the Universe opening on to the big bang itself. Particles and radiation with energies appropriate to the big bang would pour into our Universe through an ever widening hole in the sky, vaporising any galaxy that happened to be in their path.

When bubbles merge

There is no need to lose much sleep over this scenario, because Gott and his colleague Thomas Statler at the University of Princeton calculate that such a merger between bubbles in de Sitter space will occur only once in 10^{500} years. To the metaphysicists and science fiction fans, however, there is more food for thought here. The bubbles that the Princeton pair describe could all be very different from one another. The same applies to the bubbles described by Guth. In each case, the end of inflation, is linked with the breaking of symmetry between the four forces of nature; there is nothing to say, however, that the symmetry will break in the same way in every bubble. In some bubbles, the forces will have different strengths from those in our Universe; indeed, there may be three or five fundamental forces, or some other number, instead of the four we know.

Some things, presumably, must always be the same. The quantum rules that allow vacuum fluctuations to occur, the inherent uncertainty of nature, must be "universal" in the sense that they apply to all universes, not just our own. Gravity must still act to pull things together, and disorder must increase in every universe, to provide an arrow of time. But within that framework of "universals", there is still scope for a wide variety of worlds to exist. Why should the constant of gravity, G, have precisely the value it has in our Universe, for example? No one knows. Although physicists would like to think that this value is a fundamental truth that they can derive from some (unknown) first principles, there is no evidence that that is the case. It seems to be just a number, plucked out of nothing at all at the moment of creation, which just happens to determine how hard we hit the ground when we fall.

We could imagine universes in which the constant of gravity had a different value. A universe like our own, but with a smaller value of G, might be unsuitable for life as we know it. Galaxies, stars and ourselves formed in our Universe because gravity is strong enough to hold clouds of gas and dust together even though the Universe is expanding. Make G smaller, and you might be left with a universe filled uniformly with cold gas, clouds spreading ever thinner as the universe expanded, and no sign of life. If G were a little bigger, on the other hand, gravity might do too good a job of holding things together. Stars would be little hot footballs, burning their nuclear fuel frantically in a struggle to avoid being crushed by gravity. Planets (if any existed) would be proportionately small. And the entire lifetime of a star might be no more than a few of our weeks. This short period hardly gives time for evolution to produce intelligent life forms on those tiny planets.

We are back in the worlds of Arthur C. Clarke, and of those cosmologists who puzzle over the fact that our Universe seems so ideally constructed for the emergence of life—what they call the "anthropic principle". If an infinite variety of universes exists, then all things are possible. There must be infinitely many universes where gravity is too weak for life to emerge, infinitely many more where something else goes wrong. It is no puzzle that we exist, because there must also be an infinite number of bubbles in which conditions closely resemble those we see in the Universe around us. The world is, like baby bear's porridge, "just right". □